FORMULATION OF AN IPPD METHODOLOGY FOR THE DESIGN OF A SUPERSONIC BUSINESS JET

Dr. Dimitri N. Mavris
Assistant Professor & Associate Director, ASDL

William T. Hayden
Graduate Student Research Assistant, ASDL

Aerospace Systems Design Laboratory
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0150

ABSTRACT

The growth of international markets as well as business partnerships between U.S. and Asian-based firms has lead to an increased interest in an economically viable business jet capable of supersonic cruise and trans-Pacific range with one stop over (or non-stop trans-Atlantic range)[1]. Such an aircraft would reduce the travel time to these regions by as much as 50% by increasing cruise Mach number from roughly 0.85 to 2.0. In response to this interest, the 1996 AIAA / United Technologies / Pratt & Whitney Individual Undergraduate Design Competition has issued a Request for Proposal for the conceptual design of a supersonic cruise business jet. The design of this aircraft considered both performance and economic issues in the conceptual design phase. Through the use of Response Surface Methodology (RSM) and Design of Experiments (DoE) techniques, the aerodynamics of this vehicle were modeled and incorporated into an aircraft sizing code, FLOPS. This program was then combined with an aircraft life-cycle cost routine, ALCCA, and response surfaces were created for the optimization of an Overall Evaluation Criterion (OEC) which considered both mission capability (i.e. payload, range, OEW) and affordability issues (i.e. life cycle cost, acquisition cost). The OEC for this study and was determined through a Quality Function Deployment analysis considering both the voice of the customer and the voice of the engineer. Using a Robust Design Simulation (RDS) approach, an economic uncertainty analysis was performed to optimize the aircraft (i.e. maximize the OEC) while minimizing the sensitivity of these parameters to fluctuations in variables over which the designer has no control (i.e. fuel cost, number of vehicles produced, etc.). The result is an aircraft which can cruise at Mach 2.0 for 3160 nm (satisfying all mission range requirements), weighs 60314 lb, has a balanced field length of less than 7000 ft, and has a mean acquisition cost of $37.523 million in 1992 dollars.

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INTRODUCTION

In today's economic markets, the Pacific Rim is an area of constant activity[1]. Cities such as Tokyo, Seoul, and Hong Kong have established themselves as major centers of business which continue to grow every day. As a result, American corporations have developed a profound interest in the Pacific Rim. Although communications technology improves every day, multi-million dollar deals are not made over video conferencing, phone, or e-mail. Many of these business ventures require face-to-face negotiations, inspection tours, appearances by top corporate representatives to demonstrate good will and support, and other various interactions which require that employees travel between the Pacific Rim and the U.S.

As a result of this need, overseas business travel across the Pacific Ocean has increased at a rapid pace. Currently, the typical means of travel from the U.S. to the Pacific Rim is via direct commercial airline flights which travel at speeds near Mach 0.85 and therefore require roughly fourteen hours to reach their destination. In addition, some corporations have invested in their own long-range subsonic business jets which can either fly non-stop trans-Pacific missions or require a stop-over in Alaska to refuel. Although this alternative offers more comfort to the business traveler, the flight time required is often greater than that of the commercial airliners due to limited aircraft operating ranges. These long flight times are very hard on the business traveler, who must look his or her best when stepping off the aircraft in Tokyo or Hong Kong to greet representatives from an Asian-based company. As a result, air travel to, and therefore business in, this region is facing increasing obstacles to success.

One possible solution to this problem is to merely decrease the flight time required to reach the Pacific Rim from the United States by developing a supersonic business transport capable of attaining velocities in the vicinity of Mach 2.0. Traveling at these velocities, the flight time required would be cut practically in half.

Due to the focus of the aircraft industry on the bottom line, however, any attempt at manufacturing and marketing a supersonic business jet (SSBJ) must be economically viable as well as technically feasible. No corporation would purchase an SSBJ unless the aircraft was affordable as well as price competitive with existing subsonic aircraft of similar range. In addition, no manufacturer would fabricate an SSBJ unless an agreeable return on investment could be derived.

Another obstacle to the development of a supersonic business jet solution has always been a lack of sufficient technology to provide economically viable designs[2]. In the mid to late 1960's, preliminary designs began on 8 - 12 passenger trans-Atlantic supersonic aircraft (Mach number = 2.0-2.7). However, these concepts included afterburning engines and did not take noise constraints into consideration. Also during this time, the U.S. was engaged in the SST (SuperSonic Transport) national competition. Therefore, most major technological advances in the area of supersonic transports were either classified or company proprietary. The Boeing Company, however, did conduct an unpublished study of a 10-passenger supersonic jet with a 2580 nautical mile range right around the time of the SST cancellation in 1971. Soon after this cancellation, NASA launched a new research program in supersonic cruise technology (SCAR). As a result, NASA Langley Research Center and the Vought Corporation conducted design studies of supersonic business jets in 1976 using SCAR technologies. During this study, four Mach 2.2 configurations were studied and problem areas identified. Recently, the High Speed Research (HSR) program, funded by NASA with the ultimate goal of defining and producing a viable High Speed Civil Transport (HSCT), continues the search for new technologies to make supersonic cruise transport an affordable, competitive reality. Continuous technological advances such as new high lift devices, supersonic mixed flow and variable cycle turbofan engines, new materials, and new manufacturing processes have opened the door to many new design possibilities.

Therefore, technology may already exist which will allow industry to design and fabricate a supersonic business jet capable of completing trans-oceanic missions. Many of the innovations required to make this design feasible, however, have historically proven to be economically non-viable. Fortunately, technological advances being made by the HSR program will aid in bringing the cost of a supersonic transport into the economically viable range. As a result, this study, which was originally motivated by the 1995/1996 AIAA / United Technologies / Pratt & Whitney Undergraduate Individual Student Aircraft Design Competition, will focus on both the technical and economic aspects of the SSBJ in an attempt to define a configuration which will satisfy both criteria and open the gates to business in the Pacific Rim.

MISSION REQUIREMENTS AND DESIGN CONSIDERATIONS

For this study, the Supersonic Business Jet will be required to complete three different missions as stated in the AIAA Competition RFP. First, the aircraft must be able to complete a supersonic, trans-oceanic mission in order to reach Asia with a stop over in Anchorage, Alaska. In addition, the AIAA competition requirements stated that the aircraft must have the ability to reach Europe as well. Since the New York to Paris route (3160 nm) and the Anchorage to Tokyo route (3006 nm) are roughly the same distance, a design range of 3160 nm will be used which satisfies both design requirements. Secondly, the SSBJ must also be able to complete a trans-continental subsonic mission such as New York to Los Angeles. Finally, the aircraft must be able to complete an excursion mission which will require take-off and landing at airports with high elevations and short runways such as Aspen, Colorado. The supersonic and excursion missions are summarized as follows:

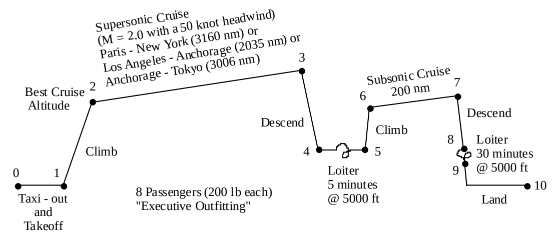


Figure 1: Mission Profile for the Supersonic Transoceanic Mission

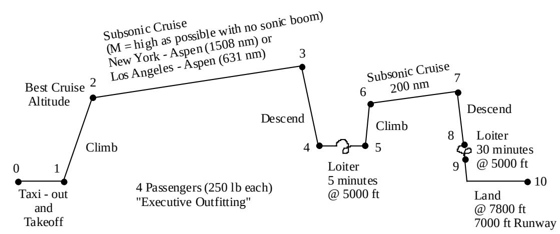


Figure 2: Mission Profile for the Excursion Mission

As shown in Figures 1 and 2, the conditions under which an SSBJ will operate present some unique design challenges. First, and most importantly, the aircraft must be designed with supersonic cruise in mind. Second, take-off and landing considerations will play a large role in the design of high lift devices employed on the aircraft. Third, provisions must be made for the storage of a large amount of fuel. Past studies have shown that the entire wing and roughly two thirds of the fuselage must be filled with fuel to complete a supersonic, trans-oceanic mission[3,4]. Fourth, horizontal tail effectiveness behind the main wing must be taken into account in tail placement. Fifth, the SSBJ will have to be economically competitive with existing subsonic corporate aircraft of comparable range. Finally, and to the customer perhaps most importantly, the main passenger cabin must be spacious and flexible while still fitting within the confines of a fuselage tailored for supersonic flight. Since all of these requirements conflict with one another, compromises and trade-offs must be made in the final design.

The first of these requirements compels the designer to optimize the configuration for supersonic cruise due to the fact that the aircraft will spend a majority of its time in this flight regime. For this study, the High Speed Civil Transport being studied at Georgia Tech's Aerospace Systems Design Laboratory was used as a guide for wing planform and fuselage shape in addition to References 3 and 4. The wing planform developed for the HSCT involves a large double-delta wing which provides the best trade-off between supersonic and subsonic operations performance. Hence, the planform used on the SSBJ will be geometrically similar yet much smaller than that employed on the conceptual HSCT. In addition to the wing, the fuselage must also be designed with supersonic flight in mind. Therefore, area ruling must be applied to the fuselage in order to minimize drag. This area ruling will be applied for the supersonic cruise condition of Mach 2.0.

Take-off and landing considerations also play an important roll in configuration development. As a result of the high lift required during these flight phases and the relatively poor lift generated by a supersonically designed wing operating at low speeds, three trailing edge and two leading edge flaps will be incorporated into the wing design. In addition, landing will require an approach angle of attack on the order of 10° in order to generate sufficient lift at velocities less than 150 KTS, which will be used as the maximum approach speed constraint in this study in an attempt to integrate with Air Traffic Control (ATC). Therefore, the SSBJ can employ either nose droop or synthetic vision technologies in order to allow the pilots clear runway visibility during approach and landing. Finally, in order to allow for flight operations from airports similar to Aspen, the balanced field length of the SSBJ must be below 7000 ft.

Fuel volume requirements also drive the design of an SSBJ. Due to the typically low thickness to chord ratio of supersonic airfoils, fuel storage capacity in the wing is minimal. Additionally, the most efficient low bypass mixed flow turbofan engines expend a great deal of fuel during supersonic operation due to high specific fuel consumptions of supersonic engines. Therefore, the fuselage must contain adequate volume to allow for the storage of extra fuel. Hence, to reduce the amount of fuselage length required to carry fuel, provisions will be made for a larger diameter fuselage than those used in previous studies[3,4]. The increase will allow for larger fuselage fuel cells and, in addition, increased passenger cabin comfort.

Effectiveness of the horizontal tail is also a major concern for an SSBJ configuration. Although the HSCT employs a horizontal tail in roughly the same plane as the wing, the distance between the trailing edge of the wing and the leading edge of the horizontal tail is relatively large due to the aircraft's elongated fuselage. Therefore, small downwash and wake effects from the wing or the wing-mounted engines impinge on the horizontal tail. The SSBJ, however, has a much smaller physical distance between the wing and the horizontal tail. Thus, the horizontal tail would encounter numerous problems such as tail fatigue and loss of tail effectiveness if it is mounted in the same plane as the wing. To avoid these penalties, the SSBJ will employ a T-tail configuration for the empennage.

Although a Supersonic Business Jet would occupy a market niche of its own, it would still have competition from aircraft which could match it in range but at a much lower cruise Mach number. In other words, any existing business jet or any business jet currently in the design stage which could fly 3160 nautical miles non-stop or further would compete with the SSBJ in the market. Therefore, these aircraft need to be identified and evaluated so that a standard of comparison can be determined. To accomplish this task, Table I has been assembled which lists all currently operational business jets, as well as those in the advanced design stage, which possess or exceed a range of 3160 nm. Also listed in this table is the aircraft's maximum ramp weight, range, cruise Mach number (or velocity), dash Mach number (or velocity), maximum thrust per engine (with number of engines in parentheses), wing span, wing area, maximum number of passengers, and cost.

Table I: SSBJ Competitors[5,6]

Aircraft	Cessna 750 Citation X	Gulfstream IV-SP	Canadair Challenger 604	Raytheon Hawker 1000	Dassault Falcon 2000
W_o (lb)	34,800	75,000	45,250	31,100	35,000
R (nm)	3,300	3,338	3,585	3,350	3,000
M_{cruise}	0.88	0.80	0.80	0.70	0.85
M_{dash}	0.90	0.88	0.83	0.87	0.87
$T_{max/engine}$ (lb) (# engines)	6400 (2)	13,850 (2)	9,220 (2)	5,200 (2)	6,000 (2)
b (ft)	63.917	77.833	64.333	51.375	63.417
S (ft^2)	531.34	950.39	520.00	374.00	527.65
$\#passengers_{max}$	12	19	19	15	12
Cost ($ x 10^6)	15.295	27.000	19.450	12.955	13.950

Perhaps the most important consideration for the passenger, however, is the size and comfort of the main passenger cabin. Previous studies[3,4] have used a low ceiling cabin in order to minimize fuselage cross-section. A functional business jet, however, must be able to transport its passengers in luxury and provide for them a spacious work area as well. These requirements, however, are in direct contradiction to the need for a minimum area fuselage cross-section to reduce the wave drag in supersonic flight. Nevertheless, the cabin must have a six foot ceiling on centerline and allow for either a twelve passenger shuttle environment (Figure 3) or an eight passenger working environment (Figure 4); complete with storage areas, a galley, and a lavatory to match the level of accommodations provided by the competition. Based on these internal layouts and results from other studies[3,4], the fuselage length and maximum diameter are 113 ft. and 7.66 ft respectively.

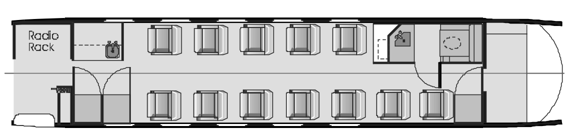


Figure 3: Corporate Shuttle Outfitting for the Passenger Cabin

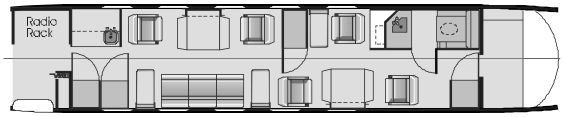


Figure 4: Executive Outfitting for the Passenger Cabin

DESIGN VARIABLES

Now that the major design considerations have been established, the focus shifts to the actual design variables which will define the SSBJ. The fuselage length and maximum diameter were sized based on volumetric requirements and are kept constant for this analysis at 113 ft and 7.66 ft respectively (note that the sectional diameter will be varied according to supersonic area ruling, but the maximum diameter of the fuselage remains constant). These dimensions allow for a spacious passenger cabin as well as sufficient fuselage volume for fuel storage.

The focus now shifts to the aerodynamics and propulsion of the aircraft. Table II lists the design variables chosen to represent these disciplines along with their definitions. These variables are graphically illustrated in Figure 5 as well.

Table II: Design Variables and Definitions

Variable	Definition
CLDES	Design Lift Coefficient
X1	Wing Leading Edge Kink x-location
X2	Wing Leading Edge Tip x-location
X3	Wing Trailing Edge Tip x-location
X4	Wing Trailing Edge kink x-location
X5	Wing Trailing Edge Root x-location
Y1	Wing Leading Edge kink y-location
SREF	Wing Reference Area
XH1	Horizontal Tail Leading Edge Tip x-location
XH3	Horizontal Tail Trailing Edge Root x-location
CTHTND	Horizontal Tail Tip Chord Length
SHREF	Horizontal Tail Reference Area
XV1	Vertical Tail Leading Edge Tip x-location
XV3	Vertical Tail Trailing Edge Root x-location
CTVTND	Vertical Tail Tip Chord Length
SVREF	Vertical Tail Reference Area
NACSCAL	Nacelle Scale Factor from Baseline
YD1	Nacelle y-location
XW	Wing Apex x-location as % Fuselage Length
XV	Vertical Tail Apex x-location as % Fuselage Length
THRUST	Thrust to Weight Ratio for the SSBJ

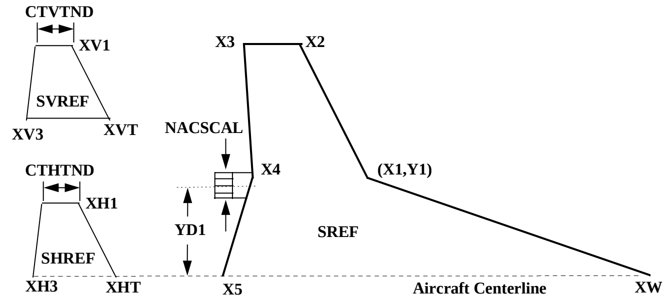


Figure 5: Geometric Design Variables

As Table II and Figure 5 illustrate, all major geometric properties are included for consideration. Note that, only the thrust to weight ratio is incorporated from the propulsion discipline. This is due to the fact that a scaleable engine deck (provided by AIAA as an RFP requirement) was used which allows the designer to completely define the engine weight, area, and length (as well as gross thrust, fuel flow rate, SFC, and nozzle exit area) with a ratio of the thrust required to the baseline maximum gross thrust at sea level. In addition, all x- and y-locations as well as the tip chord lengths are non-dimensionalized by either the wing or horizontal tail semi-span or the vertical tail span.

DETERMINATION OF THE OVERALL EVALUATION CRITERION (OEC)

Quality Function Deployment (QFD)[7] is used to define the SSBJ design challenge and establish the criterion upon which the design is to be based. This approach allows the designer to address the concerns of the customer (or voice of the customer) and correlate those concerns to product and process characteristics of the aircraft which the designer can influence (voice of the designer). These characteristics are then correlated to system criteria by which the aircraft is evaluated. In the interest of brevity, only the affinity diagrams[8] for the voice of the customer and the voice of the designer are shown.

The first step in the brainstorming process is to determine all possible groups affected by an SSBJ and to list all possible concerns they may have. These concerns result in an affinity diagram which represents the voice of the customer. This diagram is shown below:

Voice of the Customer			
Passengers	**Corporation**	**Manufacturer**	**Society**
Range	Reliability	ROI	Emissions
Speed	Maintainability	Quality Control	Noise
Safety	Passenger Capacity	Cashflow Distribution	Airworthiness / FAR 25
Scheduling / Reliability	Interior Layout Flexibility	Project Planning	Air Traffic Management Compatibility
Affordability	Utilization / Scheduling	Production	Recyclability
Comfort	Minimal Operational Complexity	Technology Level	
	Affordability	Producibility	
	Performance	Market Price	

	ROI		
	Airport Compatibility		

Figure 6: Affinity Diagram Illustrating the Voice of the Customer

As Figure 6 illustrates, the SSBJ will affect four primary customer groups: passengers, corporations, manufacturers, and society. The concerns listed for each of these groups must be examined to determine what factors will drive the design of the aircraft.

Next, the concerns of the designer must be addressed. Specifically, the factors over which the designer has control must be identified in the various discipline areas (structures, propulsion, etc.). These factors result in an affinity diagram which represents the voice of the designer. This diagram is shown in Figure 7 as follows:

Voice of the Designer			
Structures	**Propulsion**	**Aerodynamics**	**Stability & Control**
Maneuver Load Envelope	Conventional Fuel	High Lift Devices	Active Controls
Thermal Resistance	SFC	M = 2.0 Cruise	Flight Deck Design
Advanced Materials	Controlled Emissions	T.O. / Landing Distances	Fly by Wire / Light
Structural Life / Fatigue	Noise Suppression	Range	Handling Qualities
Maintainability	Nacelle Integration	Control Surfaces	
Gross Weight	T / W	Nacelles	
		Sizing / Configuration • Wing • Fuselage • Empennage	

Producibility	**Supportability**
Processes	Digital Controls
Tooling	Diagnostic System
Materials	Color Coding • Wires • Plugs

Figure 7: Affinity Diagram Illustrating the Voice of the Designer

The information contained in Figures 6 and 7 can be combined to illustrate the relationships between the customer's concerns and how the designer can respond to those concerns. Once the designer understands how his / her decisions affect the customers' needs, a means of evaluating a prospective aircraft design must be developed. For this study, the categories of affordability, capability, safety, and dependability were chosen as the areas in which to evaluate the design. Each of these areas was broken down into subcomponents such as acquisition cost, direct operating cost, etc. for affordability; range, cruise Mach number, etc. for capability, and various other sub-categories for safety and dependability. The key product and process characteristics which resulted from the correlation of the voice of the customer to the voice of the designer were then correlated to the subcomponents in the areas mentioned above in order to determine an Overall Evaluation Criterion.

The resulting QFD analysis showed that affordability and capability were the two dominant areas governing the success of the design from the customers perspective. These factors are expressed through the acquisition cost, operating cost, payload, range, empty weight, and fuel weight of the aircraft. The Overall Evaluation Criterion must reflect these considerations and can be defined by Equation 1 as follows:

$$\mathrm{OEC} = \frac{\alpha\left(\mathrm{LCC}_{\mathrm{bl}}\right)}{\mathrm{LCC}} + \frac{\beta(\mathrm{PI})}{\mathrm{PI}_{\mathrm{bl}}} \qquad (1)$$

where "bl" denotes a baseline configuration against which any new configuration is measured, PI is the productivity index which is defined by Equation 2 as:

$$\mathrm{PI} = \frac{(\mathrm{Payload})(\mathrm{Range})}{W_{\mathrm{empty}} + W_{\mathrm{fuel}}} \qquad (2)$$

and LCC is the life-cycle cost which is defined by Equation 3 as:

$$\mathrm{LCC} = \text{Acquisition Cost} + \text{Operation and Support Cost} + \text{Depreciation} \qquad (3)$$

As a result, this OEC is an excellent means of evaluation for an SSBJ configuration. In order for life-cycle cost and weight to be minimized, the OEC must be maximized. In addition, the factors α and β can be varied to reflect the relative importance of life-cycle cost and productivity index. For this study, three OECs are used with the weightings of (α,β) = (0.7,0.3), (0.3,0.7), and (0.5,0.5) respectively. Finally, the baseline configuration used for this study is a compilation of previous SSBJ studies found in references 1 through 4.

IMPLEMENTATION

A Robust Design Simulation approach is used in this study to determine the design of the SSBJ. This procedure is illustrated in the flow chart shown in Figure 8. Statistical approaches, such as Response Surface Methodology (RSM)[9,10], Design of Experiments (DoE)[10,,11], and Monte Carlo Simulation[12,13] are incorporated into the procedure, which is described in detail in Reference 14.

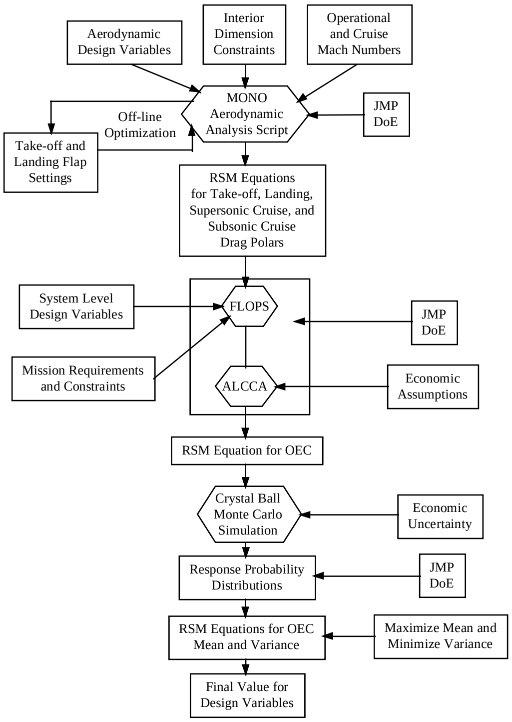


Figure 8: RDS Procedure for the Design of a SSBJ

For this design approach, Flight Optimization System (FLOPS)[15], a computer code developed at NASA Langley for multi-disciplinary optimization of an aircraft design, is employed. FLOPS can synthesize and size an aircraft for a specific mission profile. However, the aerodynamics routines in FLOPS are suitable for subsonic speeds only, due to the fact that the internal aerodynamics are based on historical data regression of subsonic aircraft. Hence these routines are incapable of generating the supersonic aerodynamic characteristics needed to size the SSBJ. Therefore, before FLOPS can be applied to this problem, it must be tailored to handle supersonic sizing difficulties. In other words, FLOPS must be able to access information on the SSBJ in several discipline areas while it is evaluating the configuration. These areas include supersonic and subsonic aerodynamics as well as propulsion, structures, stability and control, producibility, supportability, and other economic concerns. Although other discipline-specific codes exist which can be used for this purpose, it would be impractical to link them all to FLOPS for several reasons. These reasons include the length of computer run time required by these codes as well as the iterative nature of the sizing process. Therefore, a way must be found for FLOPS to calculate the information it needs based on the design variables provided as inputs to the codes.

This is where the Response Surface Methodology becomes an invaluable part of the design process. The RSE approach in essence replaces an entire computer code with a simplified polynomial equation in terms of the design variables which contribute the most to the system's response. This polynomial is based on the selected ranges for each of the design variables chosen for the supersonic business jet as shown in Table III (Please note that the wing and horizontal tail x- and y-locations have been non-dimensionalized with respect to the wing or tail semi-span respectively whereas the vertical tail locations were non-dimensionalized by the vertical tail span.). Therefore, once the RSE is incorporated into FLOPS, an SSBJ specific design tool has been created.

Table III: Key Design Variables and Ranges

Variable	Minimum	Mid-Point (Baseline)	Maximum
CLDES	0.08	0.10	0.12
X1	1.54	1.615	1.69
X2	2.10	2.23	2.36
X3	2.40	2.49	2.58
X4	2.19	2.275	2.36
X5	2.19	2.345	2.50
Y1	0.44	0.51	0.58
SREF	1050	1150	1250
XH1	0.95	1.34	1.73
XH3	1.31	1.695	2.08
CTHTND	0.29	0.40	0.51
SHREF	71	94.5	118
XV1	0.84	1.285	1.73
XV3	1.00	1.46	1.92
CTVTND	0.8	1.0	1.2
SVREF	47	72	95
NACSCAL	0.8	1.0	1.2
YD1	0.27	0.32	0.37
XW	0.22	0.25	0.28
XV	0.79	0.81	0.83
THRUST	0.27	0.30	0.33

Since FLOPS already has the capability to generate an engine deck based on the engine variable selected (i.e. values for OPR, TIT, β, etc.) the need to generate propulsion RSEs is eliminated. Furthermore, researchers at the Aerospace Systems Design Laboratory at Georgia Tech have linked together FLOPS with an economic analysis package, ALCCA[16], which eliminates the need for the inclusion of economic RSEs. Finally, FLOPS does contain a weights module which can be used in lieu of an RSE from a structures program.

AERODYNAMICS

For the aerodynamics, FLOPS requires the drag polars for different segments of an aircraft's mission such as subsonic cruise, supersonic cruise, take-off, and landing. Therefore, RSE's will be developed for the coefficients in the drag polar equation for each flight condition by first determining, through a screening test, the most significant contributing design variables. After running a screening test using JMP[17] as discussed in Reference 18, the variables which contribute most to the response are identified through the use of a Pareto Diagram[12] as shown in Figure 9.

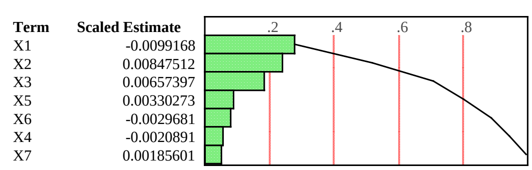


Figure 9: An Example of a Pareto Chart for Determining the Relative Contribution of Variables to the Response of a System[15]

A polynomial is then generated for each coefficient as a function of these variables. The RSE will be of the form shown by Equation 4.

$$R = b_o + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum \sum_{i<j}^{k} b_{ij} x_i x_j \quad (4)$$

where: b_i are regression coefficients for linear terms
b_{ii} are coefficients for pure quadratic terms
b_{ij} are coefficients for cross-product terms (2nd-order interactions)
x_i, x_j are the design variables
$x_i x_j$ denotes the interactions between two design variables

Before the RSEs can be generated, however, a component level Ishikawa cause and effect diagram identifying and depicting the variables which contribute to the above coefficients must be created. Once this diagram is formed, a screening test must be executed to determine the variables contributing most to the response. Then the Design of Experiments can be conducted with the pertinent design variables used in the RSE's for each of the coefficients.

The supersonic and subsonic drag polars were in the form shown in Equation 5:

$$C_D = C_{Do} + k_2 C_L^{\,2} \quad (5)$$

As a result, response surface equations were developed for the following coefficients at both cruise and operational Mach numbers:

Supersonic C_{do} => M = 2.0, 1.8, 1.6, 1.4, 1.2
Supersonic k_2 => M = 2.0, 1.8, 1.6, 1.4, 1.2
Subsonic C_{do} => M = 0.9, 0.85, 0.8, 0.7, 0.5. 0.3
Subsonic k_2 => M = 0.9, 0.85, 0.8, 0.7, 0.5. 0.3

Take-off and landing expressions for lift and drag were also required in terms of angle of attack. Therefore, the equation of the lift curve slope is used to express lift as shown in Equation 6:

$$C_L = C_{L\alpha}\alpha + C_{L\alpha=0} \quad (6)$$

RSEs are then generated for $C_{L\alpha}$ and $C_{L\alpha=0}$ at a Mach number of 0.3 for take-off and landing flap conditions. For drag, however, an RSE is generated for C_D for each angle of attack listed below:

$$\alpha = -1, 0, 1, 2, 5, 7, 9, 11, 13, 15$$

Again, RSEs for C_D were generated for both take-off and landing flap conditions. As a result, a total of 58 RSEs were generated and integrated into FLOPS. Once generated these RSEs were validated by running several different cases for design variable values not used to generate the RSEs. Results were obtained for these cases using both the RSEs and the aerodynamic analysis shell script MONO. These results were then compared in order to establish a percent error for each RSE, which never exceeded 5%.

As mentioned previously, the aerodynamic information required by FLOPS is in the form of drag polars for different portions of the mission including take-off, subsonic cruise, supersonic cruise, and landing. To obtain these quantities, a Design of Experiments must be set up around an aerodynamics tool, MONO, in order to obtain an RSE for each quantity. MONO is a shell script developed by Georgia Tech researchers which controls the flow of information through various aerodynamic codes as shown in Figure 10. The optimal planform geometry, twist distribution, and camber distribution for the SSBJ wing will be determined by WINGDES[19]. AWAVE[20] will then be used to obtain the optimal fuselage shape as dictated by area ruling. Information is then passed to AERO2S[21] in order to obtain all take-off and landing coefficients. BDAP[20,22,23] and AERO2S will then be used to obtain the subsonic cruise coefficients. Finally, BDAP will be used again to obtain the supersonic cruise coefficients. An additional off-line analysis using AERO2S will optimize the flap settings for the wing during take-off and landing.

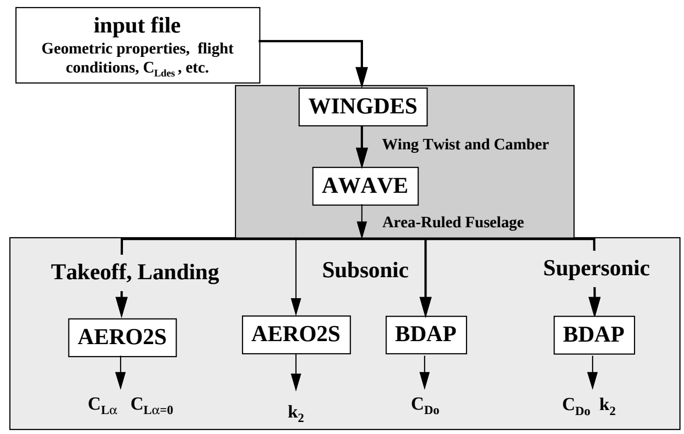
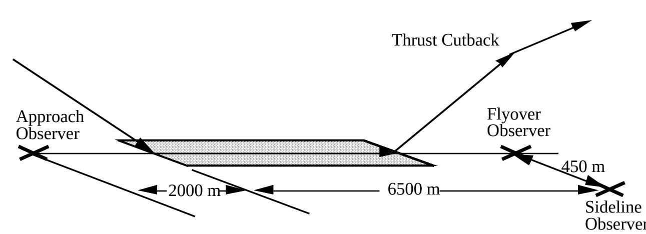


Figure 10: Linking of the Aerodynamic Analysis Codes through MONO

NOISE

To assess the environmental concerns imposed on this aircraft, the noise produced by an SSBJ must be determined as well. Noise constraints are of particular interest to the communities surrounding the airports. Currently, the Concorde is the only supersonic transport in service, and it is exempt from the mandated Federal Aviation Regulation (FAR) 36 Stage III constraints. The SSBJ, however, must abide by this regulation, and possibly Stage IV if it is to be certified by the FAA. Figure 11 illustrates the locations at which noise levels are recorded according to FAR 36 Stage III.



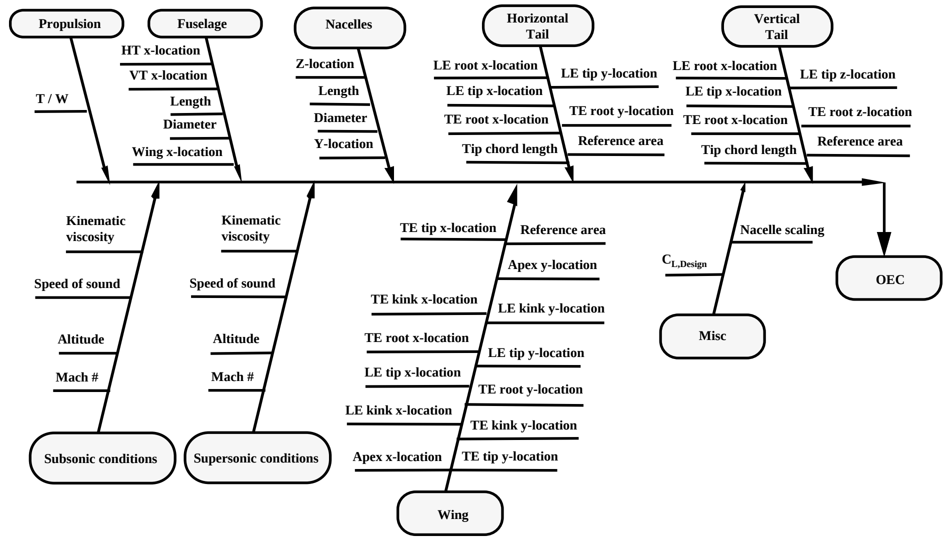


Figure 12: Ishikawa Diagram for the OEC

Figure 11: Locations for Acoustic Measurement Defined in FAR 36 Stage III[18]

Using the computer program Footprint, which has already been incorporated into FLOPS[24], the Effective Perceived Noise Level (EPNL) at the locations illustrated above can be determined. As a result of the integration of the program into FLOPS, no RSE's need to be created.

SYSTEM LEVEL EVALUATION

Now that FLOPS is bypassing internal aerodynamic calculations and is obtaining the necessary information from the response surfaces, the optimization of a configuration for maximum OEC based on the specified design variables can begin. First, however, a system level Ishikawa diagram must be generated in order to identify these variables as shown in Figure 12. The OEC is therefore a function of all of these variables.

Once the Ishikawa diagram has been completed, a Design of Experiments can be implemented around FLOPS. The design variables which contribute to the OEC must first be subjected to a screening test similar to the screening tests conducted during the generation of the RSE's. A Pareto Diagram of these variables must then be generated to determine the responsiveness of the OEC to each variable, then the most important design variables can be identified. These results are shown in Table IV. Please note that the last six variables are specified as noise variables. Noise variables introduce uncertainty and arise from economic aspects of the analysis from supply and demand needs of society. For instance, the price of fuel is constantly fluctuating and cannot be set by the designer. However, the first five variables are within the control of the designer and are denoted as control variables. In addition, the screening test showed that only these variables

Table IV: Screening Test Results for the OEC

Variable	Definition	Var. Status
THRUST	Thrust to Weight Ratio	Control Var.
SREF	Wing Reference Area	Control Var.
X1	Leading Edge Kink x-Location	Control Var.
X2	Leading Edge Tip x-location	Control Var.
X3	Trailing Edge Tip x-location	Control Var.
NV	Number of Aircraft Produced	Noise Var.
LEARN1	Manufacturing Learning Curve	Noise Var.
UTI	Utilization of Aircraft	Noise Var.
SL2	Economic Range of Aircraft	Noise Var.
COFL	Cost of Fuel	Noise Var.
RTRTN	Rate of Return on Investment for Manufacturer	Noise Var.

contributed to the value of the productivity index and the constraints. This stands to reason since aircraft weight and performance are typically not functions of economic variables. Therefore, the RSEs generated for the PI portion of the OEC and the constraints use the above five design variables. For this analysis, the design variables not included in the RSE were placed at their optimum position so as to maximize the OEC. RSEs were also generated for the life-cycle cost which included the noise variables as well as the control variables. The responses from these RSEs were then added to generate values for the OEC. These values were then used to generate response surface equation for the OEC in terms of these design variables. Therefore, the SSBJ-specific design tool has now been replaced by a single second order polynomial in terms of the specific design variables listed in Table IV. Once again this RSE was validated using the same method described previously.

ECONOMIC UNCERTAINTY

As mentioned previously, some of these variables will be beyond the control of the designer. These are known as noise variables and include quantities such as fuel price. In order to insure a robust design, the variability of the OEC to these noise variables must be minimized while at the same time maximizing the value for the mean of the OEC. It is through the minimization of the variance and the maximization of the mean of the OEC that the design becomes robust as well as optimal. This task can be accomplished through the use of a Monte Carlo simulation using Crystal Ball, which is, in essence, a random number generator code. The end result of this process is RSE's for both the mean and variance of the OEC. To accomplish this goal, different combinations of the control variables are entered according to a Design of Experiments (DoE) scheme while Crystal Ball supplies several thousand different random values for the noise variables for each combination of design variables. These random values for the noise variables are selected according to a user-defined probability distribution. A triangular distributions was assumed for each noise variable. Analyzing these thousands of different combinations of noise variables is the reason the SSBJ-specific version of FLOPS has been reduced to a single polynomial equation. Otherwise, the time required for Crystal Ball to run the combinations of noise variables necessary to create a probability distribution for each combination of control variables would be staggering. Through the use of the RSE approach, this task can be accomplished in a much shorter amount of time. For each combination of design variables, or trial, the mean and variance of the probabilistic distribution of the OEC are tracked. With these values, JMP can then create a response surface equation for the mean and variance of the OEC, based on the DoE applied. The effect of changing the control variables on the mean and variance of the OEC can then quickly be determined.

RESULTS

Once the mean of the OEC has been maximized and the variance minimized by varying the values of the design variables through JMP, the final sized aircraft configuration can be defined in terms of the design variables. Again, the values of these variables have been chosen in such a way as to maximize the OEC for the three different weighting values mentioned previously. These final values are listed in Table V.

Table V: Final Design Variable Values

Design Variable	Final Value
CLDES	0.1
X1	1.6855
X2	2.0974
X3	2.4864
X4	2.19
X5	2.345
Y1	0.58
SREF	1033
XH1	1.34
XH3	1.695
CTHTND	0.40
SHREF	94.5
XV1	1.73
XV3	1.46
CTVTND	0.80
SVREF	72
NACSCAL	0.6625
YD1	0.32
XW	0.22
XV	0.81
THRUST	0.2625

The design variable values listed in Table V resulted in a configuration for the SSBJ which not only met all mission requirements and constraints given in the RFP for the supersonic transoceanic mission and the subsonic transcontinental mission, but was also able to complete the excursion mission as well which called for flight operation from Aspen, Colorado. The final configuration, when sized for the supersonic transoceanic mission, exhibits a gross take-off weight of 60314 lb with a 113 ft fuselage and a 44.14 ft wing span. This configuration is shown in Figures 14a through 14c.

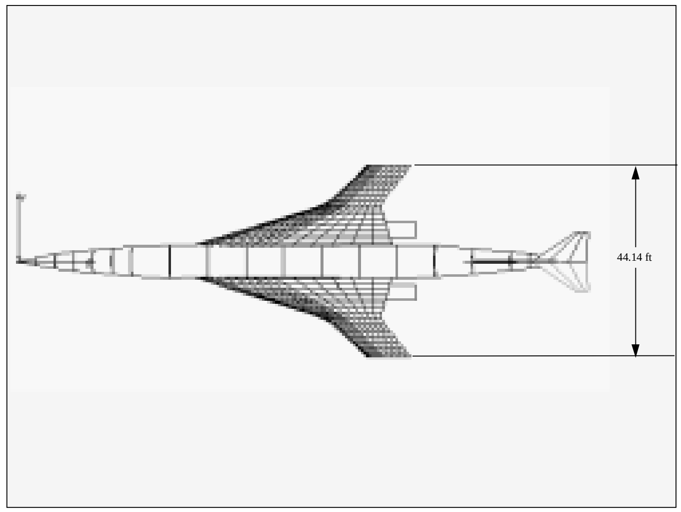


Figure 14a: SSBJ Top View

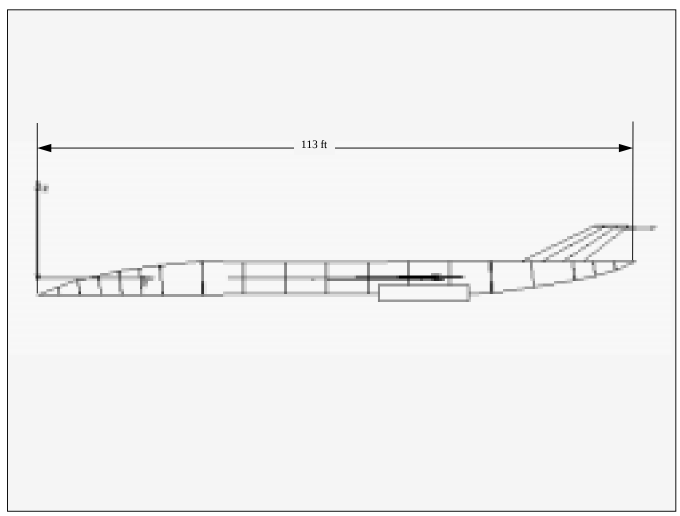


Figure 14b: SSBJ Side View

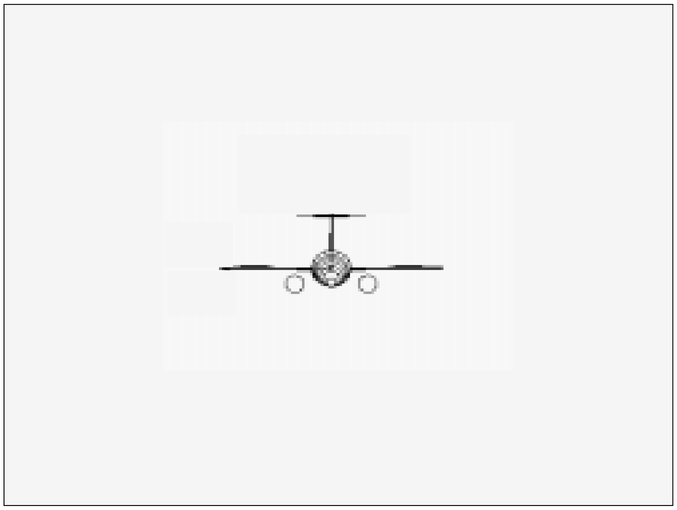


Figure 14c: SSBJ Front View

Other external dimensions as well as component details are listed in Tables VI and VII respectively.

Table VI: External Dimensions and Areas

Fuselage Length	113 ft
Fuselage Maximum Diameter	7.66 ft
Wing Span	44.138 ft
Wing Reference Area	1033 ft^2
Horizontal Tail Reference Area	94.5 ft^2
Vertical Tail Reference Area	72 ft^2
Wing Apex Distance from Nose	24.86 ft
Vertical Tail Apex Distance from Nose	91.53 ft
Nacelle Length	17.11 ft
Nacelle Diameter	2.93 ft
Nacelle Distance from Aircraft Centerline	7.06 ft

Table VII: Component Details

	Wing	Horizontal Tail	Vertical Tail
Area	1033 ft^2	94.5 ft^2	72 ft^2
Span	45.14 ft	19.00 ft	7.98 ft
Aspect Ratio	2.3 (Ref)	3.82	0.88
Taper Ratio	-	0.236	0.548
Root Chord	52.925 ft	16.10 ft	13.897 ft
Tip Chord	8.779 ft	3.80 ft	7.60 ft
Kink Chord	11.386 ft	-	-
t / c	0.030 (Ref)	0.025	0.025
Quarter Chord Sweep	65.90°, 43.50°	52.32°	33.42°
Leading Edge Sweeps	71.01°, 44.44°	54.50°	63.25°

In addition a gross take-off weight break-down is shown in Table VII.

Table VIII: Break-down of Gross Take-off Weight

	Empty Weight =	27140 lb
	Mission Fuel Weight =	29069 lb
	Unusable Fuel Weight =	615 lb
	Engine Oil Weight =	56 lb
	Passenger Service Weight =	159 lb
	Cargo Container Weight =	175 lb
	Passenger Weight (x12) =	1980 lb
	Passenger Baggage Weight =	420 lb
	Crew and Baggage Weight =	450 lb
+	Galley and Lavatory Supplies Weight =	250 lb
	Take-off Gross Weight =	60314 lb

The take-off and landing field lengths for this configuration are 4557 ft and 5823 ft respectively with an approach speed of 115.8 KTS. These performance characteristics more than satisfy the constraints which stipulate that the balanced field length shall not exceed 7000 ft while the approach speed shall not exceed 150 KTS. As mentioned previously, the SSBJ was able to operate out of Aspen, Colorado at an elevation of 7800 ft with a 7000 ft runway, even with fuel tanks fully loaded for the supersonic transoceanic mission. The variations of take-off field length and landing field length with gross take-off weight and altitude are shown in Figures 15a and 15b respectively.

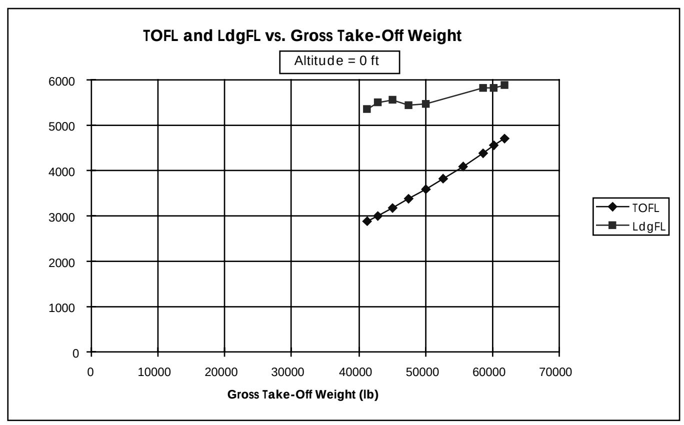


Figure 15a: Variation of Take-off Field Length and Landing Field Length with Gross Take-off Weight

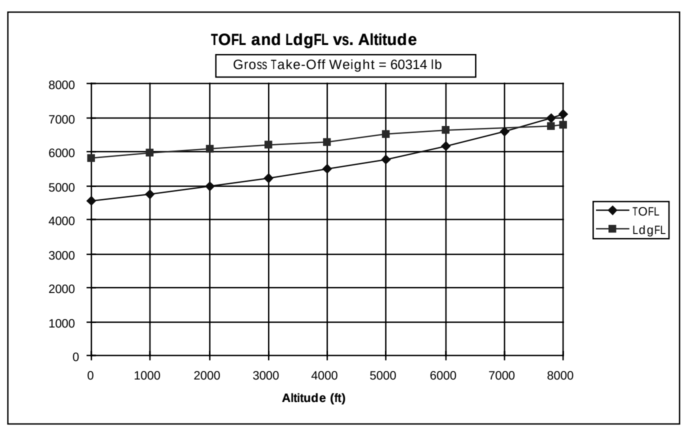


Figure 15b: Variation of Take-off Field Length and Landing Field Length with Altitude

An economic uncertainty analysis with the number of aircraft produced treated as a noise variable yielded an average acquisition cost of $37.523 million as shown in Figure 16a. When the number of aircraft produced is set at 200, the average acquisition cost is $58.84 million as shown in Figures 16b.

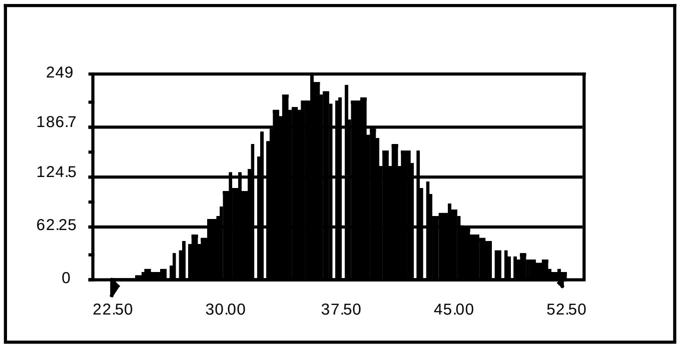


Figure 16a: Probability Distribution of the SSBJ Acquisition Cost with the Number of Vehicles Produced Treated as a Noise Variable

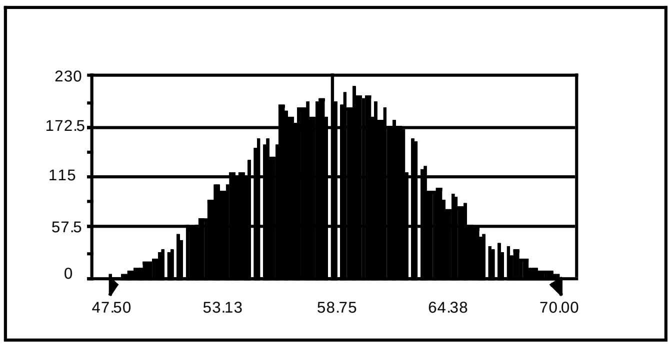


Figure 16b: Probability Distribution of the SSBJ Acquisition Cost with 200 Vehicles Produced

CONCLUSIONS

The economic viability and mission performance of a Supersonic Business Jet optimized for minimum cost and weight were the primary focus of this study which was motivated by the 1996 AIAA Individual Undergraduate Design Competition. As mentioned previously, the final SSBJ configuration was able to complete all the required missions in the AIAA RFP. In addition, it also satisfied the 7000 ft maximum balanced field length (4557 ft TOFL and 5823 ft LdgFL), the 150 KTS maximum approach speed constraint (115.8 KTS), and all FAR 36 Stage III noise requirements. These goals were accomplished while incorporating a spacious cabin equivalent in size to that of a Gulfstream G-IVSP. The mean acquisition cost for the SSBJ was projected to be $37.523 million which is 150% higher than the average acquisition cost of the competing aircraft listed in Table I. However, this cost is only 39% higher than the acquisition cost of the Gulfstream G-IVSP. Therefore, this increase represents the economic trade-off required for a cruise Mach number improvement from 0.88 to 2.00 for aircraft of comparable range.

This SSBJ is price competitive with Gulfstream G-V, which has an acquisition cost of $34 million[6]. Although this aircraft has sufficient range to fly non-stop from Los Angeles to Tokyo (6500 NM), the total flight time required for this mission is 14.5 hours. The Supersonic Business Jet can travel from Los Angeles to Anchorage, spend one hour on the ground, and fly the final leg to Tokyo in a total time of 7.7 hours. These figures represents a 47% improvement in flight time for only a 10% increase in acquisition cost. Therefore, when compared to aircraft of comparable price, the SSBJ is an economically viable alternative to the subsonic business jets currently available.

Additionally, this study accomplished the following:

1. Provided one case study of how Robust Design Simulation was applied to SSBJ concept configurations.
2. Discussed how aerodynamic information from MONO, specific to the SSBJ, was integrated into FLOPS through the use of Response Surface Equations.
3. Established the life-cycle cost and acquisition cost of an SSBJ by generating probability distributions for each.
4. Determined values for the design variables such that the SSBJ met all mission requirements and constraints.

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